The Pieninic exotic cordillera (Andrusov Ridge) revisited: new zircon FT ages of granite pebbles from Cretaceous flysch conglomerates of the Pieniny Klippen Belt (Western Carpathians, Slovakia)

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Abstract. We have studied granitoid pebbles from Cretaceous flysch conglomerates of the Pieniny Klippen Belt by means of fission-track (FT) measurements on zircon grains with the aim to reveal their low-temperature thermal history. This study contributes to the elucidation of provenance and source areas of granitoids that have been regarded as "exotic" for many decades. First data from our samples provide zircon FT ages that are close to the depositional ages of host conglomerates. The central age of one granite sample from the Albian – Cenomanian conglomerates of the Klape unit is 92.1±6.0 Ma, ten samples of the Coniacian – Santonian conglomerate pebbles from the Kysuca and/or Klape unit provided ages ranging from 89.5±7.2 to 120.8±8.8 Ma. The very short time lag of the cooling ages relative to the depositional ages of conglomerates, as well as large sizes of granitoid and various other clasts and synorogenic, thickening- and coarsening-upward character of conglomerate-bearing wildflysch formations collectively indicate that this source area was an actively deforming, exhuming and rapidly eroding mountain range with a complex geological structure.

Key words: Western Carpathians, Pieniny Klippen Belt, Cretaceous conglomerates, granite pebbles, zircon, fission-tracks

Introduction

The Pieniny Klippen Belt (PKB) is a prominent Western Carpathian tectonic structure, which separates the External Western Carpathians (EWC – the Flysch Belt), representing the Tertiary accretionary complex, from the Central Western Carpathians (CWC) that originated by Cretaceous crustal shortening and nappe stacking. The PKB is an almost 600 km long and only several kilometres wide zone with intricate tectonic structure (Fig. 1). It comprises sedimentary rock complexes of Jurassic to Tertiary age, which are affiliated to numerous tectonic and stratigraphic units. Some of these units, the Klape unit in particular, involve Cretaceous conglomerate-bearing flysch complexes traditionally treated as "exotic".

The exotic, so-called Upohlav conglomerates occur in two stratigraphic levels: Upper Albian – Lower Cenomanian, referred to as the conglomerate age Group I in the following text, and Coniacian – Lower Campanian (Group II conglomerates). These conglomerate complexes are separated by the Upper Cenomanian – Lower Turonian shallowing-upward sequence of thick-bedded sandstones with tempestites and oyster banks (Orlové sandstones) in the Klape unit. The conglomerates have a very variegated composition with numerous rock types, which were thoroughly studied and described e.g. by Mišík et al. (1977, 1980, 1981, 1991), Mišík & Sýkora (1981), Marschalko (1986), Mišík & Marschalko (1988), Birkenmajer et al. (1990), Faryad & Schreyer (1996), Faryad (1997). Besides many common rock types, the most noticeable exotic material are basinal Triassic limestones, Upper Jurassic platform limestones, Urgonian limestones with serpentinite clasts, Permian A-type granites with Lower Cretaceous FT cooling ages (Uher & Pushkarev, 1994; Kissová et al., 2004 and the present paper), large amount of calc-alkaline volcanics of uncertain age (Permian, Upper Jurassic/Lower Cretaceous?), Upper Jurassic glaucophanites (Dal Piaz et al., 1995), prevailing Cr-spinels in heavy mineral spectra (Mišík et al., 1980; Jablonský et al., 2001) etc. To explain the source of these exotic clasts, which do not occur in primary position in the PKB and neighbouring zones at all, the concept of a temporarily active Cretaceous "exotic ridge", "Klape ridge", or "Pieniny (ultra-Pieninic) cordillera" was developed many decades ago. Birkenmajer (1988) renamed this structure as the Andrusov Ridge in honour of Dimitrij Andrusov, the prominent Carpathian geologist and ever-best expert in geology of the PKB.

After the advent of plate tectonic theory, the exotic ridge has been interpreted as a compressional tectonic structure in an active margin setting – imbrications of obducted oceanic material or subduction mélange transiently outcropped along the outer structural high of an accretionary paleoprism (Mišík, 1978; Mišík & Marschalko, 1988), subduction complex exhumed in the rear part of the South Penninic – Vahic accretionary wedge (Klape unit – Maheľ, 1989), or a magmatic island arc

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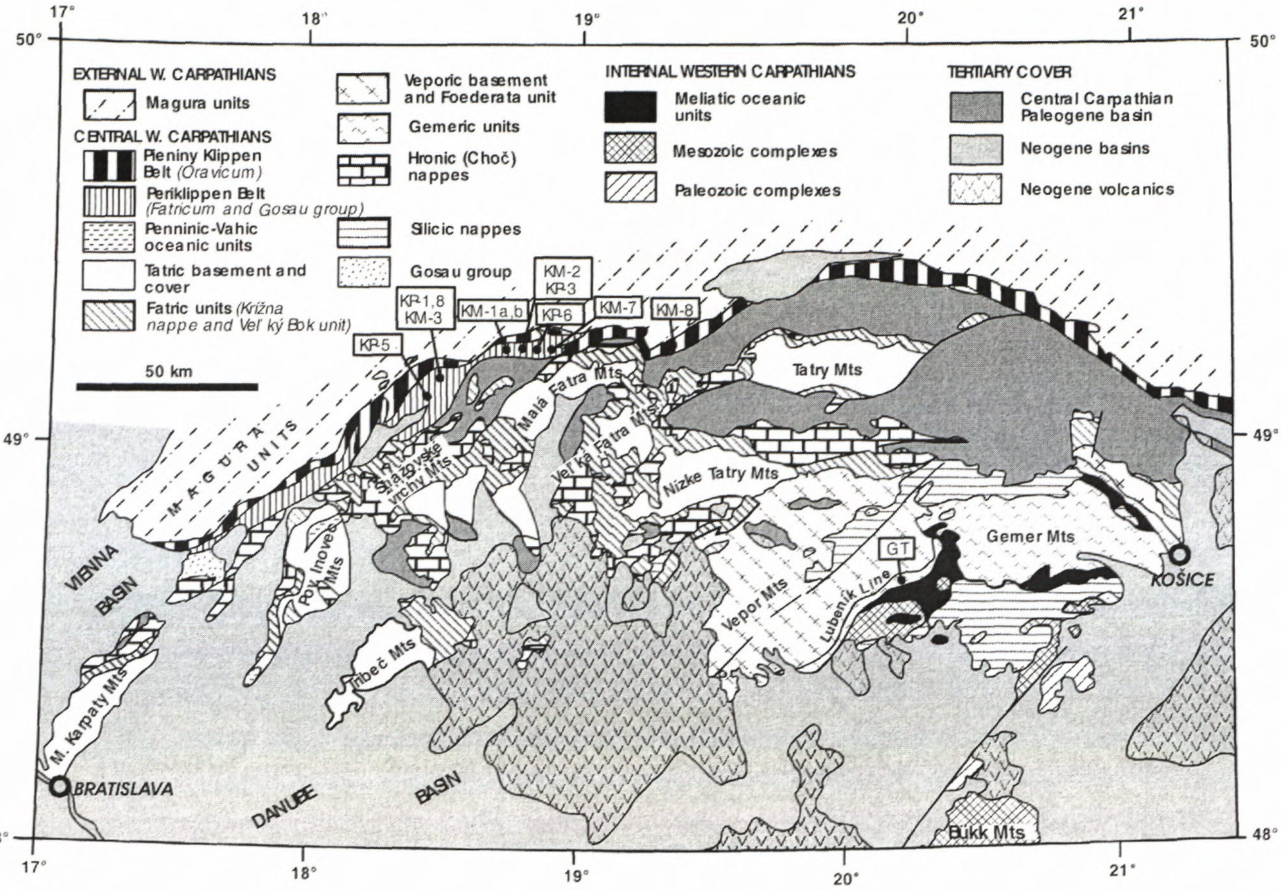


Fig. 1. Tectonic sketch of the Western Carpathians and sample location. GT marks the position of a reference sample from the Gemeric Turčok A-type intrusive granite body mentioned in the text.

(Birkenmajer, 1988). Exotic pebble material would indicate Triassic opening of the corresponding oceanic basin and its Late Jurassic – Early Cretaceous closing (e.g. Birkenmajer, 1988; Dal Piaz et al., 1995). However, this concept is in a severe contradiction with the geological record of all other PKB and neighbouring units, where no such events can be documented. On the other hand, these events surely occurred in the southern Western Carpathian zones, where they were associated with opening and closing of the Meliata ocean.

The granitoid pebbles belong to several types; the exotic character was mainly ascribed to the "Upohlav" granites with A-type petrochemical characteristics (Uher & Marschalko, 1993; Uher et al., 1994), which do not occur in potential source areas of the presently adjacent units at all. U-Pb zircon dating revealed their Permian crystallization age (274±13 Ma – Uher & Pushkarev, 1994). Similar granite pebbles were also found in the "Cenoman Randschuppe" – the most external subunit of the Northern Calcareous Alps (Frasl & Uher, 1996). Based on whole-rock K-Ar data, these granites experienced a Late Jurassic – Early Cretaceous thermal event, originally considered as an intrusion age (Marschalko, 1986; Birkenmajer, 1988 and references therein). Until now, the lower temperature thermochronological data like the fission-track (FT) zircon and apatite ages were nearly missing from the granite pebbles, as well as from the entire PKB. However, they are essential for constraining the late thermal history and cooling path of the source area and for evaluating its possible location.

The aim of our study is to identify the paleotectonic position of the source areas of the granitoid pebbles and to elucidate their exhumation histories using the zircon FT thermochronology. We classify the petrological type of granitoids from the point of view of their petrography, bulk chemistry, REE characteristics and morphology of zircon crystals. Then we employ our geochemical data and obtained zircon FT ages to discuss the provenance and possible tectonic scenarios of uplift and exhumation of the source area.

Sample location

Conglomerates with "exotic" granitoid pebbles occur in two stratigraphic levels in several units of the PKB. As it was recognized in the middle Váh valley of western Slovakia, Albian to Lower Cenomanian conglomerates (Group I – Fig. 6) are exclusively restricted to the Klape unit. On the other hand, Coniacian to Santonian conglomerates (Group II), in addition to the Klape unit, are found also in the Manín and Kysuca units. However, the stratigraphic age of some conglomerate bodies is not quite clear. This applies particularly to the Stupné locality, which according to Marschalko (1986) belongs to the

Tab. 1. Codes and coordinates of localities and sample characteristics. P – single pebble samples, MP – collection of 20 small pebbles of the same phenotype.

Code	Locality	Latitude	Longitude	Conglomerate age group	Character of samples	Petrography
KP-5	Dubový Háj	18° 21' 50"	49° 07' 20"	I	P	granite
KM-8	Oravský Podzámok	19° 21' 26"	49° 15' 24"	II	MP	granite
KP-1	Stupné	18° 25' 32"	49° 11' 37"	II	P	granite
KM-3	Stupné	18° 26' 15"	49° 11' 55"	II	MP	granite
KP-8	Stupné	18° 26' 15"	49° 11' 55"	II	P	granite
KM-1a	Divinka	18° 41' 54"	49° 15' 27"	II	MP	granite
KM1-b	Divinka	18° 41' 54"	49° 15' 27"	II	MP	granite
KM-2	Považský Chlmec	18° 44' 16"	49° 14' 49"	II	MP	granite
KP-3	Kysuca – rieka	18° 44' 21"	49° 14' 36"	II	P	granite
KP-6	Zádubnie	18° 46' 24"	49° 14' 29"	II	P	granite
KM-7	Zástranie	18° 49' 15"	49° 14' 50"	II	MP	granite

Coniacian – Santonian conglomerates of the Kysuca unit, while Salaj (1994) ranged it to the Albian – Cenomanian conglomerates of the Klape unit. We follow the opinion of Marschalko (1986) and assign our Stupné samples to the Group II conglomerates. Our sampling strategy was to study granitoid pebbles from conglomerates of both age groups to be able to reconstruct evolution of the source areas. Therefore, we collected samples from the Group I conglomerates of the Klape unit in the Púchov sector of the PKB (Dubový Háj, Upohlav) and the Group II conglomerates of the Kysuca unit in the Púchov, Varín and Orava sectors of the PKB (Stupné, Divinka, Považský Chlmec, Zádubnie, Zástranie, Oravský Podzámok). We assembled two types of samples from conglomerates: single large pebbles or population of 20 smaller pebbles of the same lithological phenotype to obtain enough material for analytical studies. The sampling localities are shown in Fig. 1 and characterized in Tab. 1.

Analytical procedure

The samples weighed 5 to 7.5 kg. Thin-sections from all samples were studied under optical microscope for the petrographical description and planimetry. The rest of the samples was prepared with the routine procedure including crushing and pulverizing of 30 g of single pebble samples. This powder was used for whole rock analysis by ICP MS carried out in laboratories of ACME Lab. (Vancouver, Canada). The rests of crushed samples were sieved (0.400 μm) and concentrated using Wilfleys' table and dried at room temperature. Further procedures included heavy liquid separation in bromoform and Na-polytungstate (>2.93 g/cm^3), magnetic separation (isodynamic magnetic separator COOK) and hand picking for determination of external zircon morphology. Scanning electron microscope was used for zircon typology. All these procedures were realized in the laboratories of the Geological Institute SAS, Bratislava.

Sample preparation for irradiation included mounting of the zircon crystals into PFA Teflon, polishing and etching. We were using grinding paper (1200 and 2500) and polishing diamond suspensions of different grain size (9 μm, 3 μm, 1 μm). The etchant for the zircon mounts was KOH-NaOH eutectic liquid used at 215 °C for 51 to 89 hours. After etching every mount was covered with flakes of low-U muscovite from India, packed using foam, polyethylene and Parafilm M and irradiated in the nuclear reactor of Oregon State University, USA. Standard of a known age (Fish Canyon Tuff and Tardree Rhyolite) and CN2 glass dosimeters with known uranium concentration were included in the sample package for irradiation and used for the calculation of a personal ζ-value (123±5.7). This part of preparation was realized in the laboratories of the University of Tübingen, Germany.

All fission track age standards and samples were counted using the same microscope setup (Zeiss Axioscope, 1000x magnification using immersion oil). The data were evaluated by the software Trackkey (Dunkl, 2002). This part of work was realized at the University of Göttingen, Germany.

Results

Petrography

Most of our pebble samples represent the Upohlav-type exotic granites as they were described by Uher et al. (1994). Granites are leucocratic, medium- to fine-grained, usually with pink, often porphyric K-feldspar. Based on petrography from thin sections and planimetrical study, the mineral composition includes quartz (Qtz) 26–40%, K-feldspar (Kfs) 34–58%, plagioclase (Pl) 6–34%, biotite (Bt) 2–13%, muscovite (Ms) <2% and subordinate microcline and epidote (Ep) <1%. Quartz is present in various forms, but always is undulating, sometimes with polygonal texture. Feldspars form euhedral and subhedral porphyric grains, typically with perthitic texture. Some feldspars are hyposolvus (Stupné, Oravský Podzámok). This feature is characteristic for the mantle-derived granites (Pupin, 1980). Sometimes poikilitic feldspar blasts (including plagioclase and quartz grains) and myrmekites were observed. Among the accessory minerals, we observed zircon, allanite-Ce and magnetite. Secondary minerals are present in every sample, represented especially by frequent fine-crystalline white mica ("sericite", mainly in cores of feldspar grains) and chlorite (after biotite). Secondary carbonates and quartz veins were observed very rarely.

For the majority of pebbles the QAP diagram (Fig. 2) reveals the trend of alkaline granites, two samples match the common granite suite. The area (3a) represents syenogranite (mineral composition: Qtz 26 %, Pl 19 %, Kfs 41 %, Bt 12 %, Ms 2 % – sample from Oravský Podzámok). Another field (3b) defines the monzogranite area (one sample from the Zástranie locality, its mineral composition is: Qtz 30 %, Pl 34 %, Kfs 34 %, Bt 2 %, Ms 0.2 %).

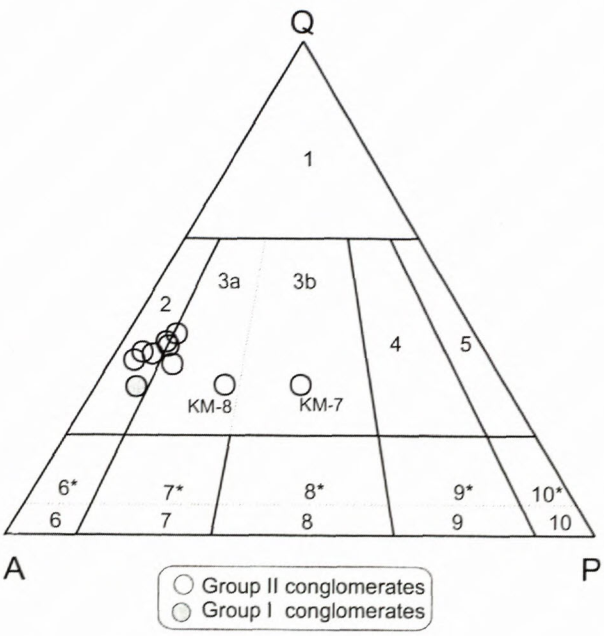


Fig. 2. Classification of granitoid pebbles according to the QAP diagram (Streckeisen & Le Maitre, 1979), the plots of investigated samples are indicated by small circles.
1 – quartzrich granitoides, 2 – alkali-granite, 3a,b – granite, 4 – granodiorite, 5 – tonalite, 6 – alkalifsp.-syenite, 7 – syenite, 8 – monzonite, 9 – monzodiorite, 10 – diorite.

Geochemistry

Detailed geochemical characterisation of the granitoid pebbles from Cretaceous flysch conglomerates of the PKB was first presented by Uher et al. (1994). We supplement their results by four analyses from three localities: Stupné (KP-1, KP-8), Kysuca – rieka (KP-3) and Zádubnie (KP-6). The whole-rock analyses of single-pebble samples are presented in Tab. 2.

The samples from all localities have a higher content of SiO_2 (70.7–75.2 wt %). Three samples have average of Na_2O 3.5 wt %, Zádubnie has a very low Na_2O content 0.09 wt %. Similar situation is with K_2O, average contents are 5.0 wt %, Zádubnie has 6.5 wt %. Content of CaO is less than 1.1 wt %, only Zádubnie includes slightly more CaO (1.5 wt %). Ba content varies considerably: the Stupné localities have 420–550 ppm, Zádub-

Tab. 2. Chemical compositions of the PKB granitoid pebbles.

		Stupné KP-1	**Stupné** KP-8	**Kysuca - river** KP-3	**Zádubnie** KP-6
SiO_2	%	74,15	73,92	70,73	75,26
Al_2O_3	%	13,16	13,12	14,15	11,69
Fe_2O_3	%	1,58	1,87	3,22	1,2
MgO	%	0,19	0,12	0,47	0,67
CaO	%	0,61	1	1,14	1,46
Na_2O	%	3,61	3,57	3,64	0,09
K_2O	%	4,96	5,08	4,57	6,46
TiO_2	%	0,13	0,14	0,31	0,11
P_2O_5	%	< .01	0,01	0,07	0,01
MnO	%	0,01	0,03	0,04	0,01
Cr_2O_3	%	< .001	< .001	< .001	< .001
Ba	ppm	415	548	977	153
Ni	ppm	< 20	< 20	< 20	< 20
Sc	ppm	10	8	14	4
LOI	%	1,4	0,9	1,4	3
TOT/C	%	0,12	0,18	0,11	0,37
TOT/S	%	0,01	< .01	0,02	0,02
SUM	%	99,85	99,82	99,85	99,97
Co	ppm	1,5	1,2	2,8	0,9
Cs	ppm	2,8	9,9	3,1	4,8
Ga	ppm	22,3	22,4	21,7	19,2
Hf	ppm	7,2	8	9,2	7,2
Nb	ppm	15,3	17,4	16,8	19,4
Rb	ppm	182,3	205,1	176,6	231,4
Sn	ppm	4	5	5	3
Sr	ppm	19,6	31,7	83,3	34,4
Ta	ppm	1,1	1,3	1,3	1,4
Th	ppm	20,4	18,8	17,1	20,1
U	ppm	2,7	2,6	3	3,1
V	ppm	< 5	< 5	16	< 5
W	ppm	9,9	9,1	7,8	6,8
Zr	ppm	225,6	266,5	316,4	214,3
Y	ppm	45,3	46	38,3	58,6
La	ppm	42,5	55,2	44,9	33,1
Ce	ppm	107,4	135,1	113,8	94,9
Pr	ppm	12,73	15,74	13,39	10,95
Nd	ppm	48,2	59,6	51,5	43,2
Sm	ppm	9,2	10,9	9,4	8,2
Eu	ppm	0,78	0,85	1,43	0,22
Gd	ppm	7,87	8,7	8,19	8,07
Tb	ppm	1,25	1,41	1,25	1,51
Dy	ppm	7,44	7,9	7,46	9,54
Ho	ppm	1,3	1,35	1,24	1,68
Er	ppm	3,91	3,95	3,89	5,53
Tm	ppm	0,62	0,6	0,57	0,78
Yb	ppm	4,28	4,5	4,35	5,54
Lu	ppm	0,61	0,61	0,56	0,75
Mo	ppm	0,1	0,2	0,1	< .1
Cu	ppm	10,2	1,5	4,8	0,5
Pb	ppm	4,7	14,5	11,1	1,8
Zn	ppm	22	63	52	6
Ni	ppm	1,8	0,5	2,4	0,5
As	ppm	1,7	2,4	1,5	2,4
Cd	ppm	< .1	< .1	< .1	< .1

		Stupné KP-1	Stupné KP-8	Kysuca - river KP-3	Zádubnie KP-6
Sb	ppm	0,2	0,2	0,2	0,1
Bi	ppm	< .1	0,1	< .1	< .1
Ag	ppm	< .1	< .1	< .1	< .1
Au	ppb	0,8	< .5	< .5	< .5
Hg	ppm	0,01	0,01	0,02	0,01
Tl	ppm	0,2	0,3	0,4	< .1
Se	ppm	< .5	< .5	< .5	< .5

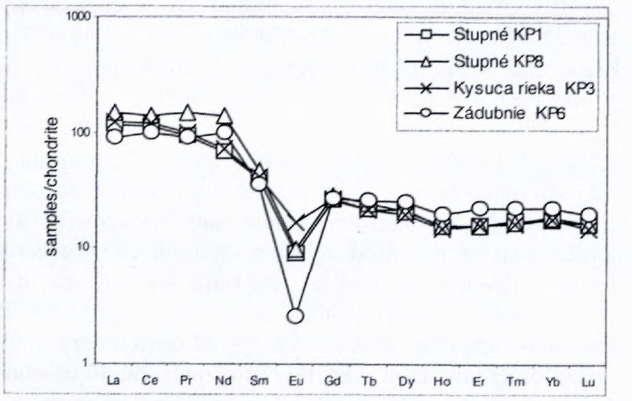
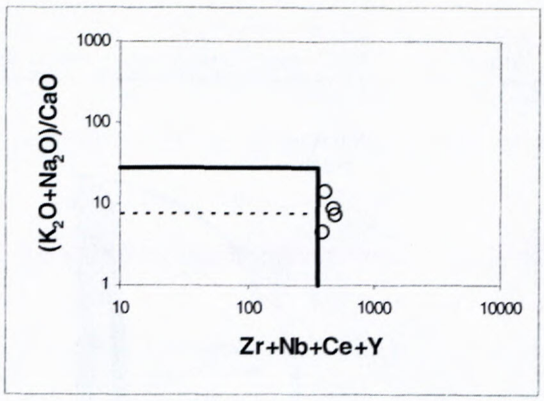


Fig. 3. Chondrite-normalized REE patterns of analysed granite samples.

nie 153 ppm, but Kysuca – rieka has an elevated content 977 ppm Ba. The reason may be secondary barite, it will be checked by the microprobe. Stupné and Zádubnie have low Sr concentration of 20–35 ppm. However, the Sr value is twice higher in the Kysuca – rieka locality – 83.3 ppm.

The rate of Eu anomaly can be quantified. The values less than 1.0 indicate negative anomaly (Rollinson, 1993), which is a typical feature for less fractionalised A-type granites and this is also our case. Our data are less than 0.35, only the Kysuca – rieka sample has a little bit higher value 0.5. Studied granite pebbles have characteristic chondrite-normalized REE patterns with significant negative Eu anomalies (0.28 to 0.5), which is a typical feature for less fractionalised A-type granites and this is also our case (Collins et al., 1982; Whallen et al., 1987 – Fig. 3). The samples are enriched in LREE (light rare earth elements). A steepness of LREE curve is determined by the La/Sm relationship. This value is usually more that 1.0, for A-type granites it is around 3.0. Our La/Sm ratios range between 2.5 and 3.18 in all samples. A-type granites are HREE (heavy rare earth elements) depleted, compared to LREE. This relationship is also characterised by steepness of the curve. It is determined by the Gd/Yb ratio, the optimal value is around 1.0–1.2. Our samples provided values 1.2–1.6 (Rollinson, 1993).

Zr+Nb+Ce+Yb vs. $(Na_2O+K_2O)/CaO$ and Zr vs. Ga/Al diagrams (Whallen et al., 1987; Fig. 4 a, b) were used for determination of the petrochemical type of granites. All our samples clearly fall into the A-type granites field. As a



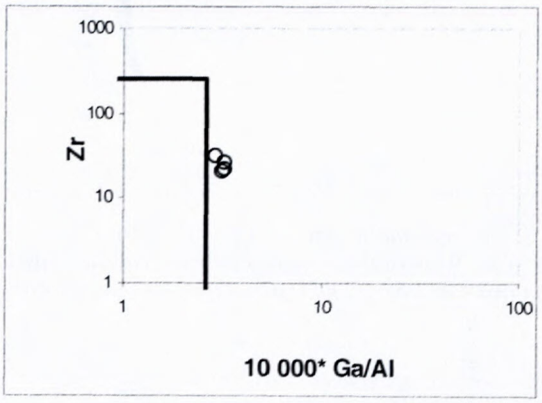


*Fig. 4. a – Zr+Nb+Ce+Yb versus $(K_2O+Na_2O)/CaO$ diagram of A-type granites and unfractionated M-, I-, and S-type granites. Co-ordinates of these fields are X=350, Y=28 (Whalen, 1987). b – 10 000 * Ga/Al versus Zr diagram of A-type granites in comparison with common ISM granites. Coordinates: X=2.6, Y=250 (Whalen et al., 1987). Our analysed granitic pebbles are shown by circles that plot in the A-type granite field.*

result, these geochemical characteristics confirm that they are post-orogenic A-type granites, according to the recent classification and knowledge (Whalen et al., 1987).

Zircon typology analysis

The typological study of zircon population (Pupin 1980, 1988) from granitic rocks resulted in the proposition of a genetic classification with three main divisions: (1) granites of crustal or mainly crustal origin; (2) granites of crustal-mantle origin, hybrid granites; (3) granites of mantle or mainly mantle origin. This method may indicate geochemical and geotectonic magma type, its relation to the orogen and indirectly characterizes the geotectonic situation in the time of intrusion (Pupin, 1980).

According to studies of Broska & Uher (1991, 2003), the Western Carpathian granitoids belong to several distinctive groups that follow the Pupin's classification (Fig. 5). All of our granite pebbles (10 samples) belong to the field of Variscan post-orogenic A-type granites (Fig. 5). The D zircon subtype (>40 %) and P_5 (20–40 %) dominates, but $P_{4\text{-}3}$ and $J_{5\text{-}4}$ subtypes are also present (5–10 %). Very rarely $S_{25\text{-}24}$ subtype crystals were found (<2 %). The relatively high A- and T-indices point to a hot and dry granitic magma probably of mantle origin (Pupin, 1980),

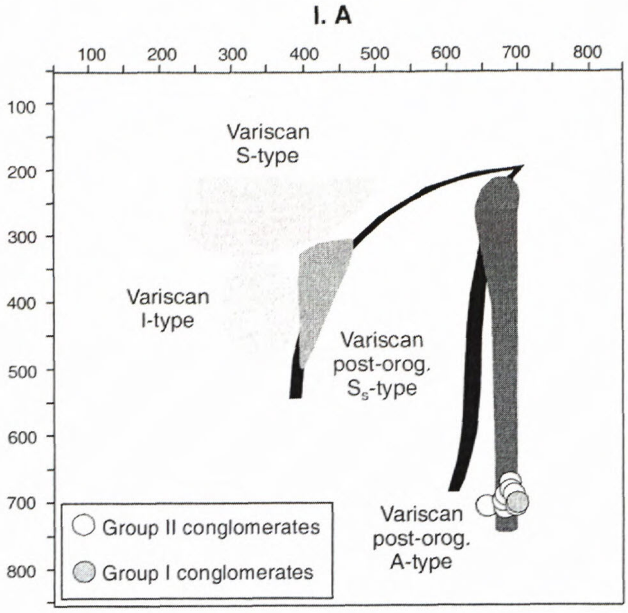


Fig. 5. Zircon typology diagram (Pupin, 1980). Characteristic fields of the Western Carpathian Variscan granitoids are taken from Broska & Uher (2003), our examined samples are indicated by circles that fall in the post-orogenic A-type granite field.

which produced hypersolvus granites with characteristic string perthites in our samples. The P and D types are common in alkaline rock (Pupin, 1980), especially in A-type granites. These alkaline and hyperalkaline granites are usually found in subvolcanic bodies of anorogenic magmatic complexes. Our observations are consistent with the first typological analyses of zircons from Upohlav-type granites, granite porphyries and rhyolites performed by Uher & Marschalko (1993).

The granitic rocks with similar zircon typologies have been described in the Western Carpathians only from a small intrusive body near Turčok (northern boundary of the Gemeric superunit – Uher & Gregor, 1992; Uher & Broska, 1996; our own unpublished data; cf. Fig. 1). As far as the zircon typology is considered, another analogous, late- to post-Variscan leucocratic, higher-alkaline granites and granite porphyries occur in the Velence Mts. (Transdanubian Range) in northern Hungary (Gbelský & Határ 1982, Uher & Broska 1996). Very similar zircon typology distribution is generally characteristic for Permian alkaline granites and rhyolites of the Western Mediterranean province, e.g. in Corsica (Pupin 1980, 1988).

Zircon FT measurements

We have analysed altogether 16 zircon concentrates from 15 granitoid pebble samples for fission-tracks. However, some samples provided not enough zircon grains, or the zircons were metamict and not suitable for FT measurements. At least 18 measured grains from single-pebble samples and 50 grains from multi-pebble samples were taken as the lowest limits for FT calculations. The inconvenient samples came mostly from other types of granitoids than A-types, therefore our whole discussion is focused on the measured A-type granitoids that yielded reliable results. The resulting calculated FT ages and measurement conditions of 11 trustworthy samples are presented in Tab. 3. Zircon FT ages of granitoid pebbles compared to the sedimentary age ranges of respective conglomerate groups are then summarized in Fig. 6.

Discussion

FT ages and erosion rates

Our data show zircon FT ages that are not very much different from the depositional ages of respective conglomerates. The cooling age of a granite sample from the Group I conglomerates (depositional age approximately 105–95 Ma according to Gradstein et al., 2004) of the Klape unit is 92.1±6.0, ten samples of the Group II conglomerate pebbles (depositional age 90–80 Ma) from the Kysuca and/or Klape unit provided ages ranging from 120.8±8.8 to 89.5±7.2 Ma. There seems to be no principal difference between the pebble ages from both conglomerate depositional age groups and, accordingly, the source area of granitoid pebbles for both conglomerate groups remained apparently at the same level of exhumation, or more probably pebbles occurring in the Group II conglomerates may have been recycled from older Group I conglomerates. However, this inference should be confirmed by additional data from Group I conglomerates.

The mid-Cretaceous FT zircon ages from the exotic granitoids are younger than and thus consistent with the Valanginian to Aptian (140 to 115 Ma) whole-rock K-Ar ages of granitoid clasts and associated volcanic rocks (Rybár & Kantor, 1978 and references in Mišík & Sýkora, 1981; Marschalko, 1986; Birkenmajer, 1988). These K-Ar ages likely correspond to exhumation and associated cooling from mid-crustal levels, thus this event might indicate crustal shortening and basement nappe stacking. However, it should be noted that the mentioned whole-rock K-Ar ages cannot be considered as fully reliable from the point of view of current standards. Because of great uncertainty in blocking temperature of K-Ar system in polymineralic rocks, the corresponding exhumation rate may be only very roughly estimated as being probably less than a tenth of mm per year (Fig. 7).

In general, we interpret the source area of the PKB Upohlav-type granitoid pebbles as an unspecified exhuming terrain that underwent a low-grade thermal event (cooling below the blocking temperatures of K-Ar system) in the earliest Cretaceous (140–115 Ma) and subsequently cooled lower than approximately 240 °C (FT zircon ages) around the Early/Late Cretaceous boundary (roughly between 110 and 90 Ma). There are several possible models that might elucidate these data. The first and preferable model A (Fig. 7) takes on the recycling concept and presumes only the Late Albian – Early Cenomanian (105–95 Ma) original deposition age of granite pebbles. Hence if we take the 95 Ma as the minimum possible primary deposition age of all pebbles, and assume the positive error bars as the maximum possible FT ages (hence not considering unrealistic negative time lags), the time lag (difference between the cooling and depositional ages) would range between 2–3 and 20 Ma.

Tab. 3. Fission track results from the granitoid pebbles of the PKB. Track densities ( ) are as measured and are (x 10^5 tr/cm^2); number of tracks counted (N) is shown in brackets; P (χ^2) is probability of obtaining χ^2 value for n degree of freedom (where n=no.crystals^{-1}); Disp. – dispersion, according to Galbraith & Laslett (1993); central ages calculated using dosimeter glass CN2 with zeta=123±5.7.

Code	Locality	Crystals	Spontaneous		Induced		Dosimeter		$P(c^2)$	Disp.	FT age*		
		numbers	rs	(Ns)	ri	(Ni)	rd	(Nd)	(%)		(Ma ± 1s)		
KP-5	Dubový háj	26	94,90	1446	57,36	874	9,09	6008	67	0,03	92,1	±	6,0
KM-8	Oravský Podzámok	60	98,01	3160	54,87	1769	9,74	6008	12	0,08	106,2	±	6,1
KP-1	Stupné	35	94,96	2763	51,52	1499	8,69	6008	0	0,18	97,2	±	6,5
KM-3	Stupné	55	74,31	2089	40,69	1144	9,05	6008	82	0,03	101,2	±	6,1
KP-8	Stupné	18	115,14	1030	72,44	648	9,49	6008	7	0,15	91,5	±	7,1
KM-1a	Divinka	60	76,08	2311	38,55	1171	8,60	6008	99	0,00	103,9	±	6,2
KM-1b	Divinka	60	104,74	3892	50,97	1894	8,65	6008	2	0,12	108,7	±	6,3
KM-2	Považský Chlmec	59	68,79	2360	37,19	1276	8,74	6008	34	0,12	98,9	±	5,9
KP-3	Kysuca – rieka	20	111,35	1412	48,58	616	8,79	6008	19	0,11	120,8	±	8,8
KP-6	Zádubnie	18	95,47	1220	56,58	723	8,84	6008	2	0,28	89,5	±	7,2
KM-7	Zástranie	54	83,53	2176	46,76	1218	9,54	6008	78	0,01	104,3	±	6,2

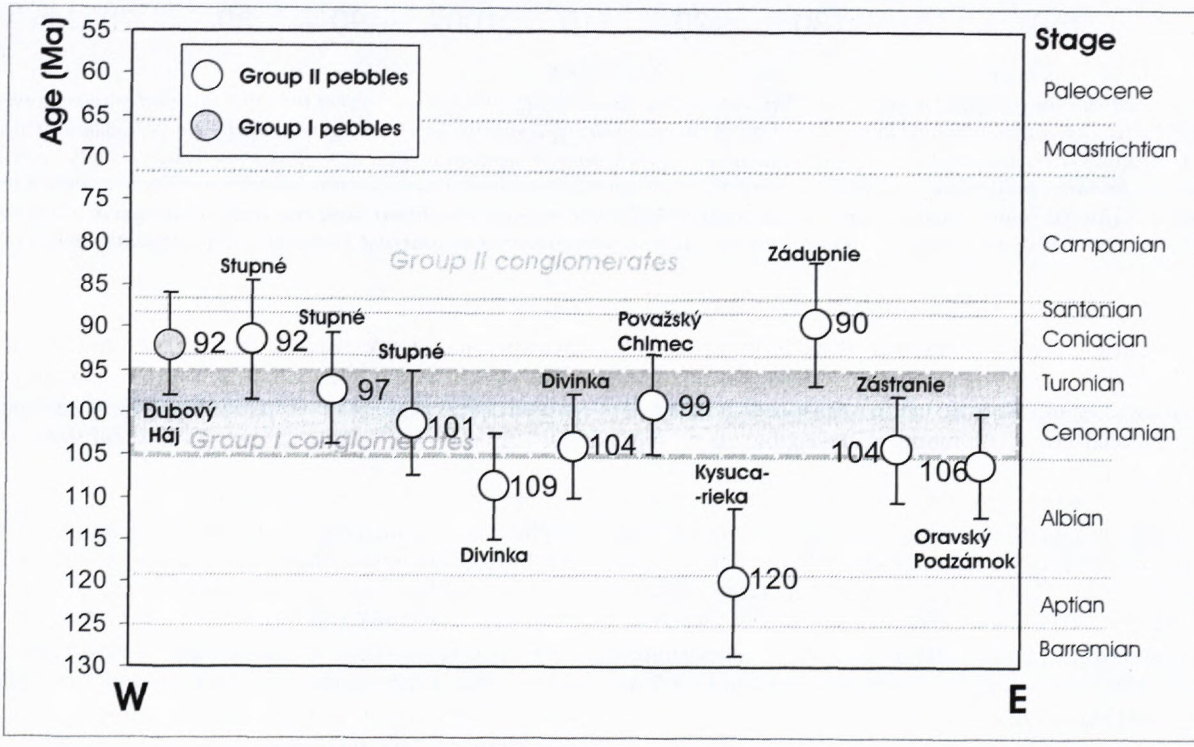


Fig. 6. Zircon FT ages of granitoid pebbles vs. the sedimentary age of conglomerate groups of the Pieniny Klippen Belt. Samples are arranged geographically from west to east.

Adopting a standard continental geotherm with a thermal gradient of about 30 °C/km in the upper crust, we obtain corresponding erosion rates between 4 and 0.4 mm per year, respectively (model A in Fig. 7). These comparatively high rates are reduced to 0.5–0.2 mm.a^{-1} (model B), however, in the case the Coniacian – Early Campanian (90–80 Ma, minimum possible age 80 Ma) depositional ages of conglomerates are considered as primary (calculating the central FT ages). If we calculate the maximum FT ages, as in the previous case, the corresponding figures are as low as 0.3 to 0.15 mm.a^{-1} (model C). On the other hand, the minimum measured FT ages (model D) compared to minimum possible deposition age would indicate erosion rates with values identical to the model A. Altogether we infer that the most realistic erosion rates of the source areas for our samples approximated 0.5 to a few mm.a^{-1}.

These adopted erosion rates are at the upper limit of those commonly referred from collisional orogens. In general, exhumation rates in excess of 1 mm/a are interpreted as being dominated by crustal extension and tectonic unroofing. Nevertheless, as pointed out by Burbank

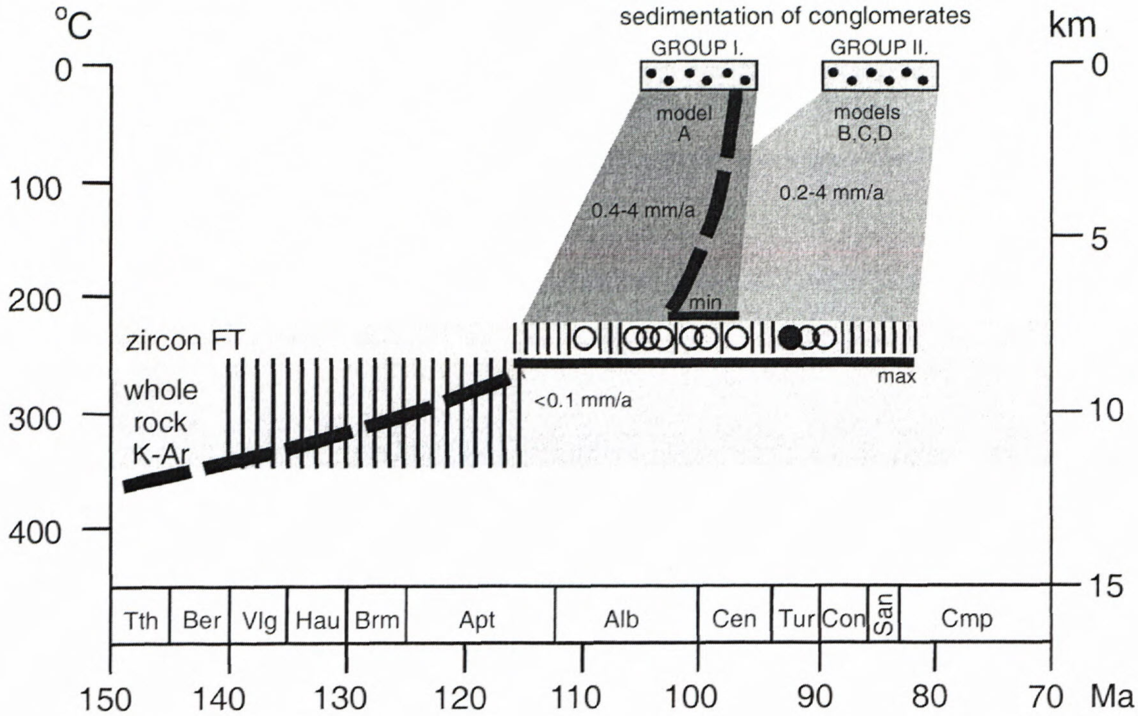


Fig. 7. Tentative exhumation diagram of granite pebbles. Central FT ages are shown by small circles (full for pebbles from the Group I conglomerates, empty for Group II). The "min" and "max" horizontal bars represent the minimum and maximum possible zircon FT ages (assuming standard deviations of track measurements), respectively. Depth estimates refer to 30 °C/km thermal gradient. Grey fields cover the possible range of exhumation/erosion rates for various models described in the text; the thick dashed line outlines the favoured path within the model A. The grey "zircon FT" area refers to the approximate closure temperature range of zircon fission-tracks, similar field labelled "whole-rock K-Ar" outlines estimated closure temperatures for Ar system in polymineralic rocks dominated by feldspars. Vertical ruling indicates the time range of measured FT ages including standard deviations, as well as the span of K-Ar cooling ages taken on from the literature.

(2002), transient erosion rates as high as 10 mm per year are still realistic and may account for high exhumation rates commonly observed in collisional orogens, even if the extensional crustal thinning is negligible. It is supposed here that the absence of mylonitic fabric in studied granitoids and indications of a high mountainous relief in source areas are signs of a compressional tectonic setting with surface erosion dominating the exhumation process in the hinterland. This is confirmed also by large sizes of granitoid and other clasts and synorogenic, thickening- and coarsening-upward character of conglomerate-bearing wildflysch formations, with boulders up to 3.5 m in diameter (Marschalko, 1986).

Possible source terrains

A-type granites with similar mineralogical and geochemical characteristics and Permian crystallization ages as those in the Upohlav-type granite pebbles occur in intrusive bodies exclusively in the southern CWC and in the Internal Western Carpathian (IWC) zones (Uher & Broska, 1996; Broska & Uher, 2000, 2001). A-type granites were interpreted as post-orogenic intrusions related to continental rifting and derived from relatively hot and dry melts. These are especially the Turčok granite in the Gemeric superunit and the Velence granite in the Transdanubian Central Range of NW Hungary. They intrude into low-grade Lower Paleozoic volcano-sedimentary complexes. On the other hand, A-type granites are completely missing in the pre-Alpine basement of the Tatric superunit, which neighbours the PKB exotic conglomerates in their present position (Fig. 1). The Tatric basement is dominated by high-grade metamorphites and synorogenic Variscan I- and S-type granites.

In spite it was known that composition of "exotic" pebbles admits their derivation from the southern Western Carpathian zones, there was seemingly no way how to transport the A-type granite pebbles, along with other exotic clasts, across the Tatric realm into flysch of the PKB area (e.g. Mišík & Marschalko, 1988). These authors stressed that there existed a wide zone with marine sedimentation and with a rugged morphology between the deposition area of conglomerates and the possible "southern" source area at the time of their deposition. These were the main arguments to construct the "Pieniny exotic cordillera" ("Andrusov Ridge" sensu Birkenmajer, 1988) – a compressional positive morphological feature that was inferred to have existed between the Klape basin and the Central Western Carpathians, i.e. in the "northern" position. The ridge should have vanished during the latest Cretaceous and earliest Tertiary when also the exotic clasts disappeared from the sedimentary record, although its younger local reactivation was possible (Neopieninic exotic ridge of Mišík et al., 1991).

Nevertheless, two other hypotheses were published that still consider the southern Western Carpathian zones as the possible source area for exotic conglomerates. According to Plašienka (1995), the Klape unit with its exotic conglomerates might represent a subunit of the Krížna nappe system that originally neighboured and received clastic material from the "southern" source terrain. In this case the Klape unit would have represented a diverticulation partial nappe of the Krížna system that after closure of the Krížna basin glided far north towards the front of the CWC nappe stack during the Turonian. An alternative view infers that the deposition realm and source areas were also originally close to each other, but they were split by a large-scale left-lateral transform fault zone along the outer CWC boundary that gradually completely separated the flysch basin from the source terrain (Rakús & Marschalko, 1997; Rakús et al., 1998), i.e. an overall conservative plate boundary setting is presumed. However, the existing structural and paleomagnetic data do not support such a scenario.

In both cases, the Group I conglomerates could have been deposited in the neighbourhood of the collisional mountain range in the southern Western Carpathian zones that formed due to the Late Jurassic – Early Cretaceous closure of the Meliata ocean. If this concept is verified, it could explain the "southern" provenance of the majority of the exotic material in the Klape flysch conglomerates, including the A-type granites.

Although the traditional concept of the "Pieniny exotic ridge" cannot be definitely excluded, its existence is highly improbable from the point of view of regional tectonics and structural evolution of the PKB and adjacent CWC zones (Plašienka, 1995). Conversely, the southern CWC and IWC zones exhibit tectonic evolution and thermochronologic data consistent with those observed in the PKB conglomerates. Therefore we still keep the working hypothesis that the source area for exotic granitoids occurred in the southern Western Carpathian zones. This opinion is based mainly on the following arguments:

- the majority of "exotic" pebbles could find their analogues and source areas in these zones without problem and similar pebbles occur also in conglomerates of the Tatric-Fatric Poruba flysch basin (Mišík et al., 1981);
- exceptional diversity of exotic pebbles point to their derivation from a collisional orogenic zone with very complex geological structure – the southern CWC and IWC zones were in a collisional setting after closure of the Meliata ocean during the Late Jurassic;
- Upper Jurassic blueschists in primary occurrences are only known from the Meliatic Bôrka nappe;
- postorogenic A-type granites with Permian to Lower Triassic intrusive ages occur only in these zones, their low-grade country rocks (phyllites, lydites, metapsamites, metacarbonates) have also some rarely occurring analogues in the PKB pebbles;
- Early Cretaceous amphibole $^{39}Ar/^{40}Ar$ cooling ages from the Gemeric basement (140 Ma, Vozárová et al., 2000) and K-Ar ages with a similar time span as in the PKB (140–115 Ma) were documented in the Bükk Mts. (Árkai et al., 1995), pointing to a very similar exhumation history;
- the Bükk, Gemer and south Vepor areas are completely devoid of Lower Cretaceous sediments, thus they were very probably uplifted and prone to erosion at that time (on the other hand, the Upper Cretaceous Gosau-type sediments occur there, though in relics only);
- the Upper Cretaceous south Veporic metamorphic core complex formed after an important Lower Cretaceous collision and thrusting event (Janák et al., 2001), most probably the Veporic superunit was overridden by the Gemeric–Meliatic–Turnaic thrust stack that provided also the pebble material for exotic conglomerates.

To evaluate this hypothesis, we measured also zircon FT ages of granitoids with Permian intrusive ages (Poller et al., 2002) from the Gemeric superunit (Fig. 1). These provided cooling ages ranging from 88.4±6.8 to 62.2±4.2 Ma (including two samples from the A-type Turčok granite that yielded 74.8 and 71.9±4.7 Ma – Kissová et al., 2004), i.e. they are mostly considerably younger than our pebble ages. The difference between zircon FT ages from PKB pebbles and present-day Gemeric outcrops may be explained by the difference in the exhumation level during mid-Cretaceous and Late Cretaceous to Recent times, respectively. An alternative view assumes that the Gemeric superunit experienced a compressional tectonic event during the Early Cretaceous, which is indicated by the lack of sedimentary record, deformation and 140 Ma thermal event (Vozárová et al., 2000); hence the area was likely uplifting and continuously eroded. This would be the first exhumation pulse culminating in mid-Cretaceous times, which was triggered by compression, surface uplift, erosion and deposition of eroded material (including exotic granitoids) in an adjacent flysch basin. After that, the Upper Cretaceous zircon FT ages of Gemeric granites were set by the heating from the hot footwall during contemporaneous extensional unroofing of the Veporic metamorphic core complex. This extensional event was accompanied also by intrusion of the Rochovce granite body into the footwall Veporic basement (75.6±1.1 Ma by U-Pb single-grain dating of zircons; Poller et al., 2001), which might annealed the original FT zircon ages in country rock complexes, including the hanging wall Gemeric granites. Accordingly, the Late Cretaceous zircon FT ages from Gemeric granites could record this second exhumation pulse associated with extension and minor surface uplift and erosion.

Tectonic scenario

The above considerations and further assumptions about the Alpidic geodynamic evolution of the Western Carpathians (Plašienka, 1999, 2002) result in a possible tectonic scenario of the source terrain and its interaction with the depositional area that is partitioned into three main periods:

1. Initial Neo-Kimmerian collision after closure of the Meliata ocean (160–150 Ma) was followed by partial nappe stacking (the Gemeric sheet overriding the Veporic) of the southern margin of the lower CWC plate of the con-

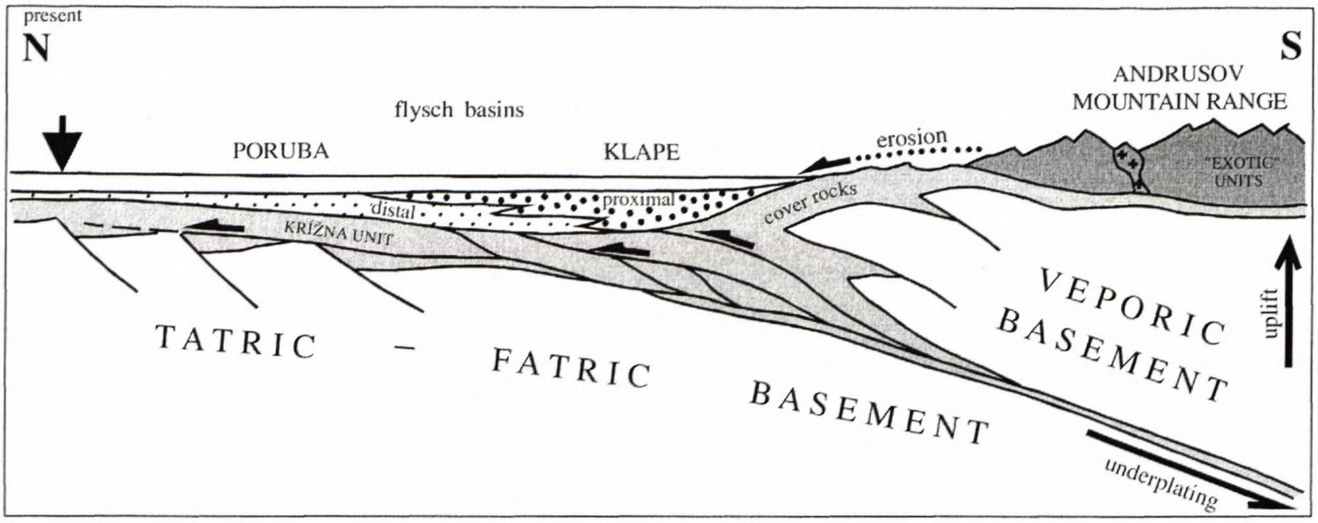


Fig. 8. Geodynamic framework of the inner Central Western Carpathian zones during the "pre-Gosauian" orogeny at around 100 Ma (Albian/Cenomanian boundary). Not to scale.

vergence system. Starting from the earliest Cretaceous (140 Ma), this inferred source terrain – the "eo-Carpathian" collisional belt, experienced gradual exhumation and non-deposition. However, the relief was likely low and smooth, since only fine-grained clastic material (often ophiolite-derived) occurs locally in siliciclastic turbiditic beds within the Neocomian pelagic marlstones in the neighbouring Krížna basin (Michalík et al., 1996). The whole source terrain experienced slow cooling and exhumation at the rate of less than 0.1 mm/a, which was fully compensated by chemical weathering and erosion.

2. By the Early Albian (around 110 Ma), shortening affected the Krížna basin, the continental basement of which started to be underthrust below the Veporic basement wedge and the overlying eo-Carpathian nappe stack. This was the paleo-Alpine (or "pre-Gosauian") orogenenic epoch (Fig. 8). As a consequence of crustal thickening, the source area was rapidly uplifting and temporarily (105–95 Ma) building up a mountainous relief that was prone to fast erosion. Exhumation rate increased considerably and the rock uplift was not more compensated by erosion, although the surface erosion intensified to some 0.5–3 mm/a. Coarse-grained erosional products, including exotic pebbles and boulders in Group I conglomerates, were deposited in prograding proximal flysch fans in the gradually shortening Krížna (Klape) basin. The Krížna basement was fully underthrust by 90 Ma and the detached Krížna nappe, including its uppermost Klape diverticulation, glided northward to cover the Tatric substratum and its foreland. After cessation of shortening, the eo-Carpathian collision stack in the source area collapsed gravitationally, mountainous relief was diminished and the Veporic metamorphic core complex was exhumed by extensional tectonic unroofing (90–70 Ma).

3. In a new allochthonous position in front of the Tatric realm, far from the original source areas, the Klape unit probably overlay the oceanic substratum of the Vahic (South Penninic) ocean, which started to be subducted beneath the Tatric basement wedge by the earliest Senonian (90 Ma). In a position of a "false" accretionary wedge the Klape unit suffered further deformation and erosion, therefore the pebble material was resedimented into the Coniacian – Santonian flysch basins developed within the same Klape and/or adjacent Kysuca and Manín units. However, these younger Group II conglomerates and olistostromes are enriched in some material derived from the neighbouring active Tatric margin (e.g. orthogneisses) and blocks of contemporaneous shallow-marine rudist reefs (Marschalko & Rakús, 1997), as well as Orlové sandstones in addition to the recycled exotic clasts. The recycling event repeated once more during the Maastrichtian and Paleocene (Jarmuta and Proč flysch formations), when the Vahic ocean closed, the CWC collided with the Oravic ribbon continent and the principal PKB units were formed.

Conclusions

We have applied a classic method of provenance studies in clastic formations – the low-temperature thermochronology of pebble material, for unravelling the exhumation history and probable location of the source area of Cretaceous conglomerates of the Pieniny Klippen Belt of Western Carpathians. It has been long known that most of this material does not occur in the presently adjacent tectonic zones at all, hence the pebbles and their hypothetic sources were described as "exotic" already in early thirties of the previous century (Zoubek, 1931). It is therefore not surprising that our first zircon FT data from granitoid pebbles show ages, which cannot be considered as recording exhumation and cooling processes that might have been operating within an orogenic zone neighbouring the actual position of the PKB.

Results of our zircon FT age determinations and their consequences for the provenance and tectonic evolution of the source area are summarized in the following points:

- It has been confirmed by bulk petrography, geochemistry, REE content and study of zircon crystal morphology that the studied granitoids belong to the A-type anorogenic granites, which are very similar to the Turčok and Velence granite bodies occurring in the southern Western Carpathian zones, but are completely missing in units currently adjacent to the PKB. All these A-type granites share similar post-Variscan, generally Early Permian crystallization ages.

- One sample from the Group I conglomerates of the Klape unit exhibits an age 92.1±6.0 Ma; the upper limit of 98 Ma is considered as the most realistic to match the depositional age of conglomerates that should not be younger than 95 Ma. In any case, a very fast corresponding erosion rate up to several mm per year has to be taken into account.
- Nine samples from the Group II conglomerates scatter between 89.5 and 120.8 Ma central ages. Since the single age from older conglomerates falls within this age range, we tentatively suppose that all studied pebbles were originally resting in Group I conglomerates and were later partially recycled into younger conglomerates. This assumption would again infer high erosion rates.
- The available K-Ar data (though poorly reliable) and our FT data indicate a slow Early Cretaceous exhumation of the source terrain, which was considerably increased in one order of magnitude during erosion and deposition of the synorogenic conglomerates. We ascribe this increase to a temporary accumulation of compressive stresses that triggered surface uplift and mountain building in the source areas.
- All these data and inferences coincide well with the thermotectonic history of the southern Western Carpathian zones, where a similar succession of tectonic events may be documented. We therefore see no need for construction of a totally hypothetical structure, the Pieniny exotic cordillera or Andrusov Ridge, as the source area for the exotic pebble material. Problems with transport ways of exotic material from their sources to apparently very distant deposition place may be readily avoided by some tectonic process, e.g. by a nappe transport of conglomerate-bearing Klape unit as a constituent of the Krížna nappe system (Plašienka, 1995). The post-nappe Group II conglomerates show some features of resedimentation from Group I conglomerates – our FT data rather support than contradict to the recycling concept.

Nevertheless, it is clear that our first age data show some scatter, which calls for the need of a denser database. Processing of a new set of samples is in progress and will hopefully clarify some still ambiguous points in our existing data, especially concerning the age data from the Group I conglomerates, because only one successfully completed measurement is clearly insufficient for definite conclusions. Consequently, the discussion and conclusions presented here may be considered as preliminary only.

Acknowledgement

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